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The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO_2 emissions

Dries Haeseldonckx, Leen Peeters, Lieve Helsen, William D'haeseleer*

Department of Mechanical Engineering, University of Leuven, K.U. Leuven, Belgium

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Abstract

When evaluating the environmental impact of small-scale cogeneration facilities, two important boundary conditions are often overlooked. Firstly, cogeneration units are mostly considered as stand-alone facilities, although, in reality, they will be part of a system that may also contain a thermal-storage tank and back-up boiler. Secondly, usually mainly static and simplified methods are used to calculate the possible reduction of CO_2 emissions. In this paper, these issues are discussed in two parts. The dimensioning of cogeneration facilities to fulfil a certain heat demand and the impact of thermal-storage tanks on the operational behaviour of these units are dealt with. It is shown that the use of thermal-storage tanks prolongs the yearly operation time of a CHP facility and allows the cogeneration unit to operate more continuously. Also, it is clarified how to interpret thermal load-duration diagrams in a correct way. Furthermore, the impact of thermal storage on the overall CO_2 emissions is investigated. Hereby, the interaction with the expansion of the central power system and the annual use of the cogeneration units are two important parameters. Using a small thermal-storage device causes the net reduction of CO_2 emissions, in comparison with a reference scenario without additionally installed cogeneration, to be almost three times higher compared to the case without heat buffer. Finally, it is shown that the operational behaviour of multiple small-scale cogeneration units can be approximated by the behaviour of one large fictitious unit for the determination of the net reduction of CO_2 emissions.

Keywords: Small-scale cogeneration; Dimensioning; Thermal storage; CO_2 emissions

*Corresponding author.
E-mail address: william.dhaeseleer@mech.kuleuven.be (W. D'haeseleer).

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1. Introduction

Nowadays, from a technical point of view, micro-cogeneration units such as gas turbines and gas engines are quite well developed. Despite their not always favourable economics, which can partly be overcome by governmental subsidy programmes or other support mechanisms, mainly environmentally driven arguments may serve as a stepping-stone towards the massive introduction of small-scale cogeneration facilities for residential use [1,2]. It is expected that small cogeneration may contribute to the reduction of CO_2 emissions. However, two major errors are made too often when evaluating the ecological impact of these units [3,4].

Firstly, cogeneration units are mostly considered as stand-alone facilities, although, in reality, they will be part of a system that may also contain a back-up boiler and a thermal-storage tank. Whereas back-up boilers merely serve to fulfil peak demands and low-level demand if the CHP facility cannot operate well beyond its full-rated level, the use of thermal-storage units may influence the operational behaviour of the CHP facility and, therefore, the resulting environmental characteristics.

Secondly, usually mainly static and simplified methods are used to evaluate the ecological impact of CHP facilities. In order to draw a truthful picture of the environmental benefits cogeneration can bring about, the dynamic interaction between the cogeneration systems and the central power system, and the dynamic response of the cogeneration facilities themselves, possibly influenced by the use of thermal-storage devices, have to be taken into account.

In this paper, the two issues above will be discussed in detail. The first part deals with the dimensioning of cogeneration facilities to fulfil a certain heat demand and considers the impact of thermal-storage tanks on the operational behaviour of CHP units. For each

specific situation, the output of a CHP facility is simulated on an hourly basis during one year, taking into account the dynamic behaviour (start up, shut down).

The second part discusses the effect of the massive introduction of micro-cogeneration, in combination with thermal-storage units, on the overall CO_2 emissions. In contrast with the static and simplified method, the dynamic interaction with the central power system is taken into account.

Earlier work related to the dynamic aspects of massive introduction of cogeneration includes the papers by Voorspools and D'haeseleer [4,5]. The present work focuses on the changes due to thermal storage units.

2. The impact of thermal storage on residential cogeneration units

2.1. General guidelines for dimensioning CHP units

The potential energy savings and emission reduction, resulting from the massive introduction of small-scale cogeneration, largely depend on the boundary conditions that determine the operational behaviour of these facilities. Namely, in order to fully benefit from the energetic and environmentally added value that the use of CHP facilities can offer, these units must be run in a heat-driven way. However, a technical problem may arise when CHP installations are operated in a fully (heat-)load-following way, including peak loads. In this case, the CHP facility has to be dimensioned to cover the maximum heat demand and the operational behaviour will be similar to that of a conventional residential boiler. This would cause the CHP unit to be switched on and off—or to ramp up and down when operation at partial load is possible—very frequently, resulting in transient behaviour that may have a negative influence on the lifetime and decrease the possible energy savings.

Therefore, unless deliberately used as a back-up electric power supply unit, CHP facilities can be operated in combination with auxiliary devices such as back-up boilers and thermal-storage tanks. For technical and economic reasons, the installation of an additional boiler is always desirable. As a result, the CHP unit can be dimensioned to cover an "average" thermal-power demand instead of the maximal heat-power demand.[1] The back-up boiler then serves to provide the peak demand and the low thermal load levels, well below acceptable operation levels of the CHP unit.

Another solution to mitigate the somewhat negative effects of thermal-load following can be offered by the use of thermal-storage devices. This will allow the CHP unit to operate more continuously and, consequently, avoid frequent occurrence of transient behaviour during start-up and shutdown. It will also permit to extend the operational time of the CHP facility, which is translated by more energy savings and larger CO_2 reductions.

2.2. Concrete dimensioning of cogeneration facilities

In order to properly dimension residential CHP facilities, 40 different residential heat-demand profiles have been created out of a set of measured data [6]. An example is given in

[1] As will be explained in Section 2.2, "bare' CHP units are to be dimensioned to operate at thermal power levels such that the amount of heat energy delivered by the CHP is maximal (integrated over a particular time period; e.g., 1 year).

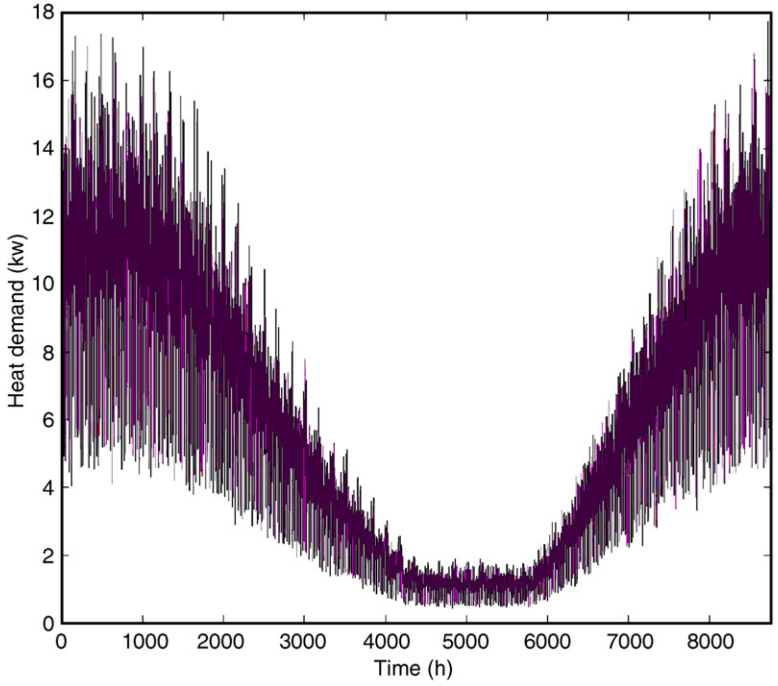


Fig. 1. Residential heat demand throughout the year (example for a particular dwelling and household).

Fig. 1. The dimensioning itself is based on the 'biggest rectangle' method [7]. The 8760 heat-demand values are sorted in descending order and placed in a load-duration diagram, as represented in Fig. 2.[2] Subsequently, the biggest rectangle that can be inscribed in the load-duration curve is determined (dashed line). The intersection of this rectangle with the vertical axis then represents the optimal value for the rated thermal power of the CHP facility to be used to fulfil this specific heat demand. In all cases investigated in this paper, this dimensioning method has been used to determine the size of CHP facilities.

Although the introduction of thermal buffers may lead to different prescriptions with regard to the dimensioning of a CHP facility, this paper sticks to the conventional largest-rectangle method, to better demonstrate the effects of thermal-storage systems on the energy savings and CO_2 reduction.

2.3. Parameterised CHP simulation model

In order to determine the operational behaviour of residential CHP units during 1 year, a parameterised simulation model has been developed. The reference setup used for the

[2]By inscribing the largest rectangle in this load-duration diagram, it is assured that a CHP facility of rated thermal power A, that operates during B (usually not continuously connected) hours, produces the maximum amount of thermal energy (being the time-integrated power). If it is assumed that the cogeneration unit cannot operate at partial load and that no thermal-storage buffers are used, the both areas a and b are covered by a so-called back-up boiler.

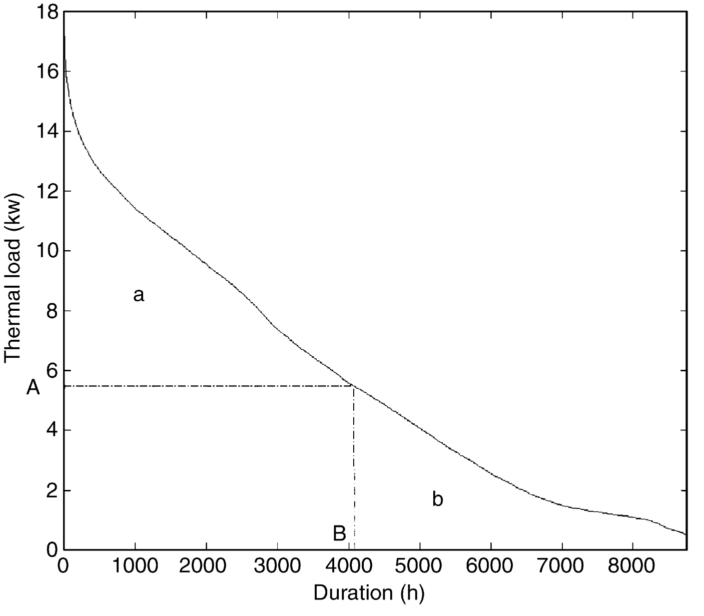


Fig. 2. Load-duration diagram.

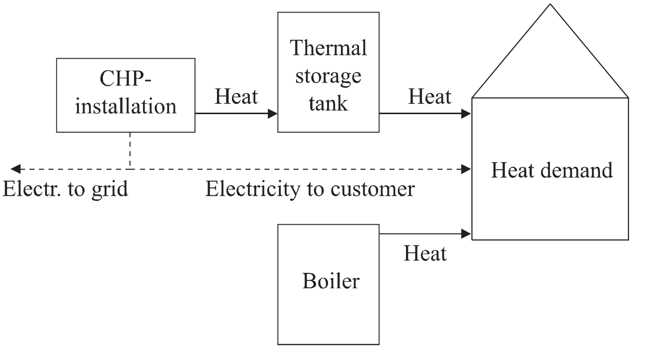


Fig. 3. Configuration of CHP facility, boiler and thermal-storage tank.

calculations is represented schematically in Fig. 3. The chronological hourly heat-demand profile during 1 year and the entire system (CHP unit, storage tank, boiler and ducts) characteristics are the only input parameters to the simulation programme. The input system characteristics include all stationary thermal and electric power outputs and efficiencies, the transient characteristics of the CHP installation and boiler, the heat capacity and heat losses of the thermal-storage tank and the efficiency of the heat transport through the ducts. All characteristics of the CHP facility were measured on a 5.5 kW_e SenerTec gas engine (see e.g. [5]). For determination of the other characteristics, a Viessmannn boiler and storage tank have been used.

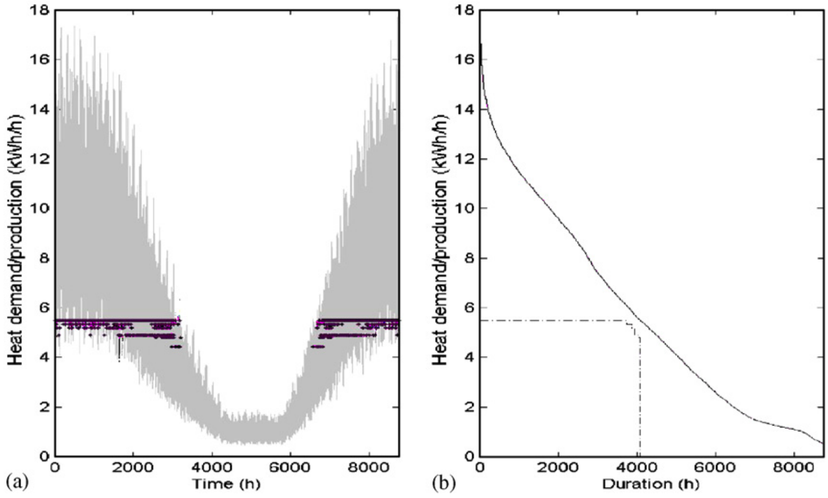


Fig. 4. Chronological (left) and load-duration (right) diagram of the hourly heat demand and production throughout the year without thermal storage.

Every simulation starts on the 1st of January at 0.00 h and ends on the 31st of December at 24.00 h. In the beginning of a simulation run, the CHP unit is considered to be shut down and the heat content of the storage tank is 50% of its maximum capacity. The CHP facility is turned on whenever the heat content in the storage tank becomes less than 20% of the maximum capacity. It is switched off when the storage tank is completely full. The back-up boiler, in turn, is switched on to provide additional heat when the heat content of the buffer and the heat generated by the CHP facility cannot satisfy the hourly heat demand.

2.4. The operational behaviour of CHP facilities with and without thermal storage

2.4.1. CHP facility without heat storage

The working regime of a CHP facility when no thermal-storage tank is available is quite straightforward. The cogeneration unit is switched on whenever the hourly heat demand exceeds the amount of heat the CHP facility can produce in one hour.[3] Otherwise, the boiler is used to fulfil the heat demand and it also provides the heat needed above what the CHP can deliver. The hourly heat demand and heat production by the cogeneration unit, are given in Fig. 4a. The solid grey line represents the chronological residential heat-demand profile, whereas the black dots represent the amount of heat produced by the CHP facility during the corresponding hour on the horizontal axis. In this case, a CHP facility with a thermal power of 5.7 kW has been installed. It can be noticed that the cogeneration unit does not produce the same amount of heat every hour, although it is always running for an entire hour (when it is switched on). This is due to the transient start-up effects. Namely, a CHP facility that is switched on after several hours of (cold) standstill, will

[3]Because the simulation programme divides the year in 8760 h, and the time unit is 1 h, a heat load or thermal power of $x\,kW_{th}$ equals an amount of heat energy of $x\,kWh_{th}$ delivered during that 1 h.

produce less heat during that hour than when the CHP facility has been continuously running the foregoing hours.

Fig. 4b is a different reproduction of the operational behaviour of the CHP unit whereby both the hourly heat-demand and hourly heat-production data have been sorted in descending order. Here again, transient start-up effects cause the CHP facility to produce less heat during some hours, which results in a 'rounded' corner of the rectangle inscribed in the load-duration curve. Not taking transient effects into account would have resulted in a perfect rectangle.

2.4.2. CHP facility with the possibility to store the heat produced during 1 h at full load

In order to correctly determine the influence of a thermal-storage tank on the operational behaviour of a cogeneration unit, the same heat-demand profile and CHP facility as above are used. The hourly heat demand and heat production are given in Fig. 5a. The capacity of the thermal-storage tank considered here is such that it is possible to store the amount of heat produced by the cogeneration facility during 1 h at full load. The effect of thermal storage is threefold:

(1) The cogeneration unit is able to store excess heat and thus, is allowed to operate when the hourly heat demand is lower than the amount of heat the CHP facility can produce in 1 h, as long as the storage tank is not entirely filled. As can be seen in Fig. 5a, this results in a higher operating time of the CHP unit, since operation during summer, when heat demand is generally low, becomes possible.
(2) Thermal storage allows the CHP facility to operate more continuously. Whereas the cogeneration unit has to be switched on and off very frequently when no thermal storage is available, it can now operate continuously and store excess heat during periods when heat demand is low.
(3) When evaluating the CHP behaviour during one specific time interval, e.g. 1 h, it can occur that the CHP facility does not operate for the entire time interval. Namely,

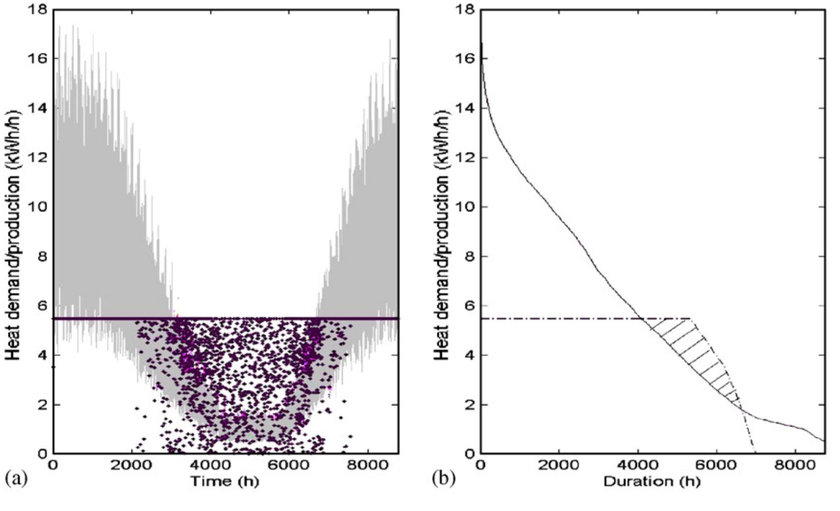


Fig. 5. Chronological (left) and load-duration (right) diagram of the hourly heat demand and production throughout the year with the possibility to store the heat produced during one hour at full load.

without thermal storage, the CHP facility is switched on at the beginning of an hour, according to the corresponding heat demand during that hour (and is assumed to operate during that full hour). With thermal storage, the working regime of the CHP facility is dictated by the energy content of the thermal-storage tank. So, when this energy content drops below 20% halfway an hour, the cogeneration unit will be switched on at that very moment, working only 30 minutes during that hour.[4]

Fig. 5b again represents the load-duration curves of the heat demand (solid line) and heat production (dashed line) by the CHP facility. This figure deserves some extra attention, since it is often interpreted erroneously. Intuitively, one might think that the shaded part represents the amount of heat that is stored in the thermal buffer, and that this stored heat is used to fulfil the heat demand in the lower-right corner of the graph (the part where the heat produced is less than the heat demand). Yet, since both curves on Fig. 5b do not represent data in a chronological, but a descending order, no conclusions of this kind can be drawn. Namely, none of the points of the heat-production curve is chronologically correlated to the point of the heat-demand curve that lies above or beneath it on the load-duration diagram. Therefore, one is unable to state anything concerning the amount of heat that is stored, or regarding the time when this stored heat is used.

Furthermore, in contrast to Fig. 4b, the values of the heat-production curve, lower than the maximal hourly thermal output of the CHP facility, do not only result from the transient start-up characteristics of the CHP facility. They are, in this case, mainly induced by the fact that the CHP facility is allowed to work for periods less then 1 h, which, of course, leads to less heat production during that particular hour.

2.4.3. CHP facility with the possibility to store the heat produced during two hours at full load

During this simulation, all parameters are kept identical to those of the two previous cases, except for the energy content of the thermal-storage tank, which is doubled compared to Section 2.4.2. The only difference with the simulation above is that the threefold effect (see Section 2.4.2) of using a thermal-storage tank is even more pronounced. In Figs. 6a and b, it can be seen that the CHP facility operates more frequently and continuously, especially during summer. The number of switches on and off are strongly reduced, resulting in less transient behaviour throughout the entire year. This effect is also represented by the steeper slope on the right-hand side of the heat-production curve in Fig. 6b. However, the overall operation time of the CHP unit is not very different from the previous case in Fig. 5b.

2.5. The impact of thermal storage

Until now, the simulations discussed in this paper, were all carried out for one specific residential heat-demand profile. In order to verify the tendencies above, several simulation runs have been performed, using different heat-demand profiles and, therefore, different sizes of CHP facilities and thermal-storage tanks. The three residential cases are as follows:

[4]The vertical axis of Fig. 5a should really be read as kWh/h and not merely as kW. Indeed, the CHP unit still only runs at full load (and not at partial load), but it can operate for fractions of an hour because of the extra degree of freedom provided by the thermal-storage tank.

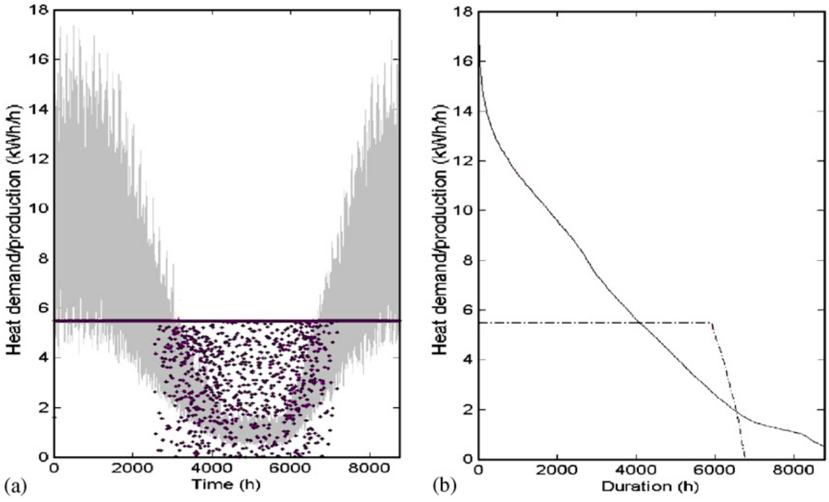


Fig. 6. Chronological (left) and load-duration (right) diagram of the hourly heat demand and production throughout the year with the possibility to store the heat produced during two hours at full load.

case 1 is a rowhouse, inhabited by two employed parents and one schoolgoing child; case 2 is a semi-detached house, inhabited by one employed and one unemployed parent and by two schoolgoing children; case 3 is a stand-alone house, inhabited by one employed parent and one school-going child. Each of these cases has its own specific hourly heat-demand profile, resulting in different sizes of the CHP unit to be installed (according to the largest-rectangle dimensioning method) and a different operational behaviour of these cogeneration facilities. Whereas the difference between cases 1 and 2 is obvious—higher heat demand, thus higher installed thermal power—the difference between cases 1 and 3 seems rather contra-intuitive. The lower installed thermal power in case 3, however, results from a heat-demand profile that shows fewer peaks than the one in case 1. Therefore, the installed power according to the largest-rectangle method lies closer to the hourly averaged heat demand. The results are summarised in Table 1 below.

Firstly, it has to be mentioned that the number of switches cannot be seen separately from the yearly operating time. Namely, rather than the absolute number of switches in one year, it is the switching frequency (number of switches divided by the operating time) that is important for the lifetime and transient behaviour of the CHP facility. Once it is turned on, a cogeneration unit should operate as long as possible without interruption. Therefore, the lower the switching frequency, the better.

It can be clearly seen that the impact of thermal storage on the switching frequency and operating time of a CHP facility during one year, is quite similar in every case. Installing a small thermal-storage tank causes the switching frequency at first to rise slightly. This is due to the possibility for the CHP facility to operate during summer.[5] Each time the heat

[5]The heat demand during summer time is mainly for sanitary water needs (and some sporadic space heating on "colder" days). It is not the purpose of this paper to optimise the heating behaviour during summer (i.e., to figure out whether the CHP facility should operate rather than e.g. the back-up boiler), but to explain the impact of storage devices if it is assumed that the CHP unit operates as explained in this section.

Table 1
Impact of thermal storage on CHP behaviour

	Residential case 1		Residential case 2		Residential case 3	
Yearly heat demand	24,934 kWh		50,493 kWh		26,475 kWh	
Thermal power CHP	3.00 kW_{th}		5.50 kW_{th}		2.58 kW_{th}	
Thermal storage capacity	Operating time (h)	Switching frequency	Operating time (h)	Switching frequency	Operating time (h)	Switching frequency
None	3706	0.25	4071	0.20	4462	0.16
Heat produced during 1 h	6130	0.29	6351	0.26	6610	0.24
Heat produced during 2 h	6210	0.14	6411	0.13	6661	0.12

"Switching frequency" is defined as the number of switches in one year divided by the annual operating time.

buffer is almost empty, the cogeneration unit will be switched on until the heat buffer is entirely filled. When the size of the buffer is increased, it will last longer to fill it up and to use all the heat that is stored. This, in its turn, results in a switching frequency that lies well below the situation without thermal storage. A still further increase of the storage capacity only has a minor impact on the switching frequency.

As far as the operating time is concerned, even the installation of a small thermal-storage tank leads to an increase of approximately 2400 h per year. This effect is only slightly enhanced when a larger heat buffer is used. As a conclusion, it may be expected that the use of a thermal-storage tank is quite favourable, as it allows a more efficient use of the CHP facility, but there is no sense in over dimensioning the thermal-storage unit, or in using buffering devices that are too small. These statements are backed up below by numerical results on energy savings and reduction of CO_2 emissions in Section 3.

2.6. The overall behaviour of massively installed CHP facilities

When the overall impact of residential cogeneration on CO_2 emissions is looked at, clearly the effect of more than one single unit has to be taken into account. Therefore, it is interesting to check whether or not the overall operational behaviour of a large number of residential cogeneration facilities significantly differs from that of one single unit (as discussed above). Furthermore, the question can be raised whether it is possible to use a modelling approximation whereby the behaviour of several smaller cogeneration units is "mimicked" by the behaviour of one large fictitious unit, which is able to fulfil the same overall heat demand.

Suppose a yearly heat demand of 22 GWh has to be covered by the use of residential cogeneration. This would cover approximately 1000 households in the climate region of North-West Europe (i.e. approximately Belgium and The Netherlands). The overall heat-demand profile for these households is represented in Fig. 7. According to the biggest-rectangle dimensioning method, one (fictitious) large CHP facility with a thermal power of 2540 kW_{th} would be needed to fulfil this heat demand. The behaviour of this large unit, with and without thermal storage, is completely identical to the behaviour described in the previous paragraphs (Figs. 4–6).

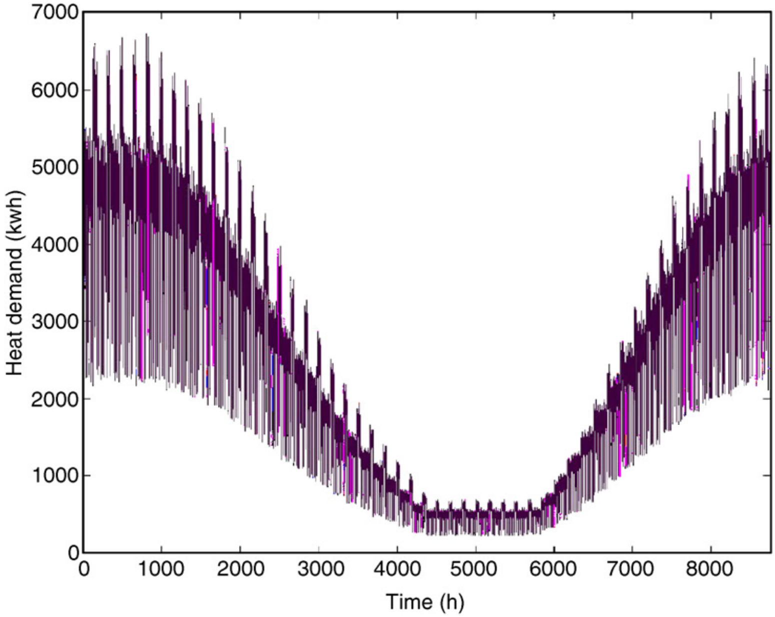


Fig. 7. Residential heat demand of 1000 households throughout the year, in the climate region of North-West Europe.

In reality, however, the yearly heat demand of 22 GWh is covered by 1000 separate and smaller CHP facilities, each with their own specific operating regime throughout 1 year and each of them dimensioned to fulfil one single household's heat demand. After going through the CHP dimensioning for each of the set of 1000 dwellings, whereby we have considered 40 different types of dwellings and households, the total-installed thermal power of these 1000 facilities turns out to be 2450 kW_{th}, somewhat less than when, hypothetically seen, one larger unit would have been used. But, rather than the small difference in installed thermal power, it is the overall operational behaviour throughout the year that deserves some extra attention.

To obtain this overall operational behaviour, the actual thermal power output of each individual CHP facility is simply added. Again, three different cases have been looked at: firstly, CHP facilities without thermal storage, then with a thermal-storage capacity equal to the amount of heat produced during 1 h and finally with a heat-buffer capacity equal to the amount of heat produced during two consecutive hours. Both the chronological and load-duration curves for each case are represented in Fig. 8. Remarkably, but with hindsight not unexpectedly, the overall operational behaviour of 1000 small-scale residential CHP facilities looks as if it is one large cogeneration unit that can work at partial load. It therefore gives the impression of a large fictitious unit that is able to follow the heat demand as good as possible.

Indeed, analysis of the simulation results clarifies that this apparent load-following behaviour is merely "an illusion". Namely, during a certain hour, some of the 1000 residential cogeneration units will be working at full load, while others will not be running at all. Adding them up creates the impression of one large CHP facility working at

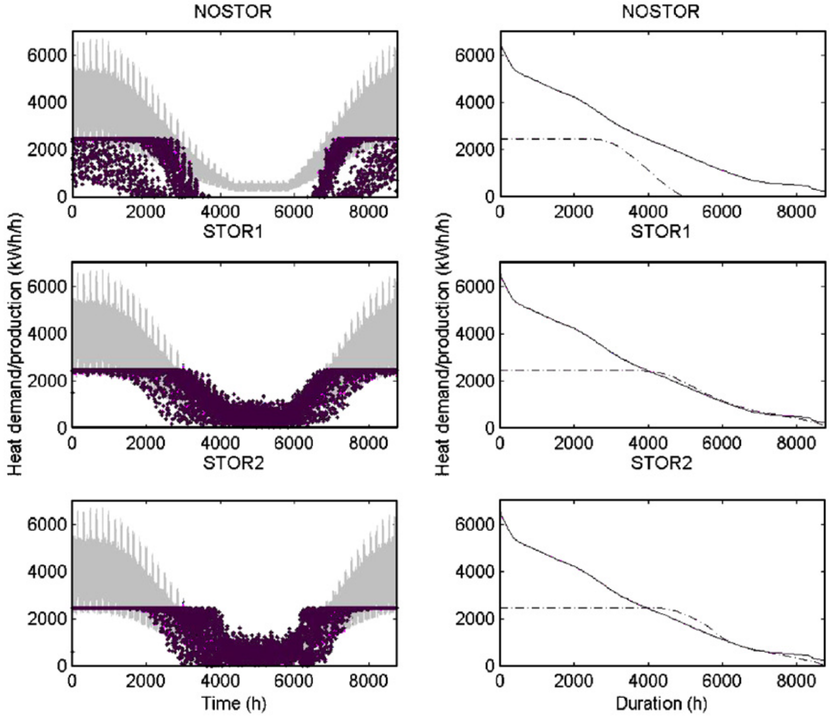


Fig. 8. Chronological (a) and load-duration (b) diagram of the overall hourly heat demand and production of multiple small-scale CHP facilities. Without storage (NOSTOR), with the possibility to store the heat produced during 1 h (STOR1) or during 2 h (STOR2).

partial-load conditions, but in reality it is just the average behaviour of a large amount of small-scale units.

Table 2 below summarises the differences in installed thermal power and yearly operating time between the 'one fictitious large facility' and the '1000 small-scale facilities' approach. Although the operational behaviour resulting from each approach differs significantly, as can be seen by comparing Figs. 4–6 with 8, the numerical differences for the installed power and the operation time seem to be rather small. Nevertheless, when evaluating the impact on the overall CO_2 emissions, and thus the interaction with the central power system, we still have to compare the results of both approaches. Of course, the overall behaviour of a large number of small-scale CHP facilities bears much closer resemblance to reality, but for the sake of computer time economics it would be convenient to verify that the 'one fictitious large facility'-approach also leads up to trustworthy results. This comparison is the subject of Section 3.

3. The impact of thermal storage on the overall CO_2 emissions

3.1. The dynamic system approach

As mentioned before, mainly static and simplified methods are used to evaluate the ecological impact of CHP facilities. Because of the flaws in these methods, a more dynamic

Table 2
Differences in installed thermal power and yearly operating time between one large CHP facility and multiple small-scale facilities

	One large facility	Multiple small-scale facilities
Installed thermal power	2540 kW	2450 kW
Thermal storage capacity	Operating time (h)	Operating time (h)
None	3831	3912
Heat produced during 1 h	6219	6262
Heat produced during 2 h	6296	6338

method, developed and described by Voorspools and D'haeseleer [4,5], is used. In this approach, the entire energetic (electricity and heating) context is simulated. For heating, the hourly heat demand in the residential sector is used and CHP units are heat-demand driven, complemented with boilers when necessary. For electricity, the model PROMIX is used to simulate the electricity generation on an hourly basis and on a power plant level. The CHP units are electrically modelled as "must run"; i.e., whenever electricity is generated by the CHP units, that amount no longer needs to be provided by the centralised system. The central system operates here in a "master–slave" relationship, whereby the central system must behave as the slave. In this way, the dynamic interaction with the central power system is properly taken into account. This approach is represented schematically in Fig. 9.

3.2. Hypotheses and boundary conditions

For each scenario, it is assumed that, by 2010, 6707 GWh of residential heat demand is to be fulfilled by using small-scale cogeneration (and back-up boilers when needed). When the simulation approach of one large fictitious CHP facility is used, this results in one cogeneration unit with an electrical power output of 360 MW_e and a thermal power output of 783 MW_{th}. On the other hand, when the overall operational behaviour of thousands of small-scale cogeneration facilities is considered, this results in an overall installed electrical power of 347 MW_e and an installed thermal power of 755 MW_{th}. The operational behaviour for both scenarios, depending on the amount of thermal storage installed, is calculated as discussed previously in this paper.

The time horizon of all cases is 2010 and the energetic context is Belgian. The energy prices used are those as projected by the IEA World Energy Outlook in 2004 [8]. In 2010, the Belgian electric system is assumed[6] to consist of nuclear power plants (5700 MW), combined-cycle gas-fired plants (6000 MW), coal-fired plants (800 MW), other thermal units (1800 MW of which about 800 MW is fired with blast furnace gas or coke oven gas), renewable power plants (260 MW, including waste), water pumping units (1300 MW) and cogeneration (1700 MW, mainly in industry).

[6]Because of uncertainties in a liberalised market, this means that the electricity system has effectively been "postulated" for our purposes. For our methodological purposes, the exact details of the system compared to reality in 2010 is not important.

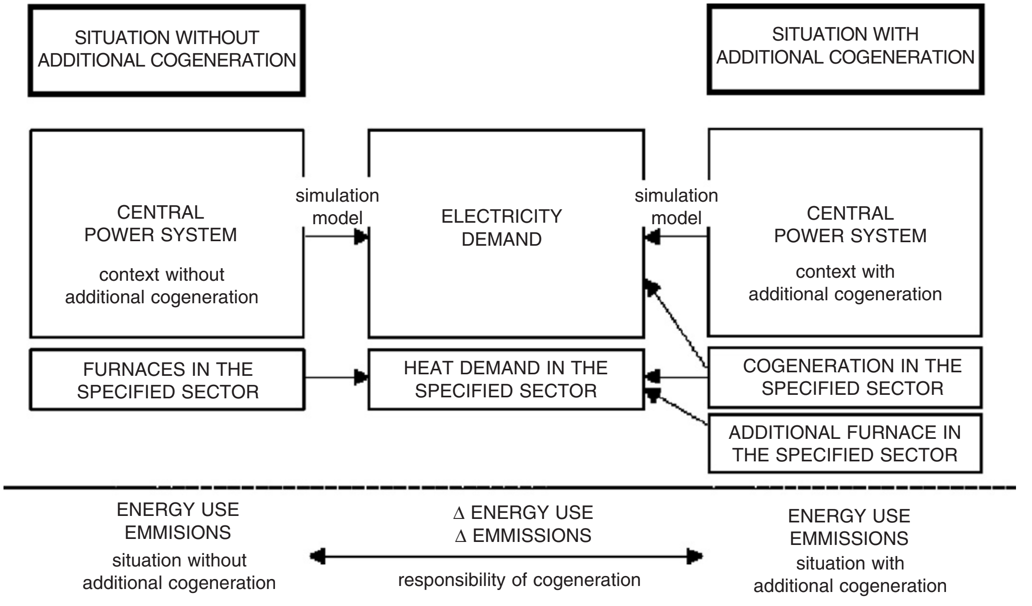


Fig. 9. Method for the evaluation of cogeneration [5].

If the operation of the cogeneration units coincides with the peaks for overall electricity demand (in winter during daytime), these peaks will be alleviated for the central system and the need for new power plants will be reduced. This will be the case in all of the scenarios considered, since the cogeneration units operate in a heat-driven way and heat demand is also highest in winter during daytime. Since the newly installed amount of cogeneration can generate 360 MW_e (one large unit) or 347 MW_e (lots of smaller units) of electricity, the commissioning of a comparable power station can be avoided. In the Belgian context, this will be a combined cycle gas-fired unit of 400 or 386 MW_e, respectively (with smeared out reliability of 90%).

All scenarios with additional cogeneration are compared to a reference scenario. This reference scenario is the "business as usual scenario". However, it has to be noticed that this scenario is only a reflection of the plausible evolution of the energetic parameters for the near future. A detailed analysis of these parameters can be found in [9].

3.3. One large fictitious cogeneration facility—the impact of thermal storage

Three different scenarios are investigated here. In each scenario, the operational behaviour of the additionally installed amount of residential cogeneration is calculated as if one large fictitious CHP facility with an electric power of 360 MW was installed. Each scenario mutually differs from the others by the amount of thermal storage that is installed.

In the first scenario, referred to as LARGE_NOSTOR, no thermal storage has been installed. In the next two scenarios, called LARGE_STOR1 and LARGE_STOR2, one large thermal-storage tank with a capacity of 783 and 1546 MWh_{th}, respectively, has been installed. The results of these simulations are shown in Table 3.

Table 3
The impact of thermal storage on the overall CO_2 emissions—one large CHP facility

2010		Reference	Large_nostor	Large_stor1	Large_stor2
Annual use cogeneration (h/a)		——	3,831	6,219	6,296
Electricity generation (GWh_{el})	Central	95,277	93,898	93,038	93,010
	Cogeneration	——	1,379	2,239	2,266
Heat production (GWh_{th})	Furnaces	6,707	3,707	1,907	1,867
	Cogeneration	——	3,000	4,835	4,905
Primary energy use (TJ)	Central electric	821,150	813,320	806,920	806,590
	Furnaces	26,829	14,828	7,656	7,497
	Cogeneration	——	18,526	30,135	30,478
	Saving	——	1,305	3,268	3,414
Greenhouse-gas emissions ($kton_{CO_2-eq}$)	Central electric	27,556	27,091	26,702	26,693
	Furnaces	1,558	861	444	435
	Cogeneration	——	1,076	1,750	1,769
	Reduction	——	86	218	217

From Table 3, the beneficial effect of using thermal storage as far as the energy savings and CO_2-emission reduction are concerned can be clearly seen. Without thermal storage, the use of residential cogeneration only seems to bring about a small ecological advantage, namely a yearly saving of only 86 kton CO_2. The advantage of using thermal storage becomes clear by comparing LARGE_NOSTOR with LARGE_STOR1. In the latter case, the reduction of CO_2 emissions amounts to 218 kton/year, compared to the reference scenario. This effect remains unchanged, when the thermal-storage capacity is doubled (LARGE_STOR2). Of course, this improvement is totally due to the prolonged operating time of the CHP facility, which is directly coupled to the installation of thermal storage, as discussed previously. These results clearly confirm the point already made by Voorspools and D'haeseleer [4,5] with respect to CHP operation time, but our work here demonstrates that CHP-residential heating only makes sense with the use of thermal storage.

3.4. *Multiple small-scale CHP facilities—the impact of thermal storage*

In the next three scenarios, the operational behaviour of the additionally installed amount of CHP is calculated as the sum of the individual behaviour of approximately 300,000 small-scale cogeneration facilities. This overall behaviour was obtained by simulating the behaviour of CHP facilities for 40 different dwellings and households, each having its own heat demand, and then scaling up the results to 300,000 households.

Again, the three scenarios mutually differ by the amount of thermal storage that is installed in each household and are referred to as SMALL_NOSTOR, SMALL_STOR1, SMALL_STOR2. In this case, thermal-storage tanks are placed in every household with the ability to store the heat produced by the corresponding CHP facility during 1 or 2 h. The simulation results are shown in Table 4.

Again, the same tendencies as above can be observed. There is a small net reduction of CO_2 emissions when no thermal storage is used. With thermal storage, the reduction of

Table 4
The impact of thermal storage on the overall CO_2 emissions—multiple small-scale CHP facilities

2010		Reference	Small_nostor	Small_stor1	Small_stor2
Annual use cogeneration (h/a)		——	3,912	6,262	6,338
Electricity generation (GWh_{el})	Central	95,277	93,919	93,104	93,078
	Cogeneration	——	1,358	2,175	2,201
Heat production (GWh_{th})	Furnaces	6,707	3,752	2,044	2,007
	Cogeneration	——	2,955	4,696	4,762
Primary energy use (TJ)	Central electric	821,150	813,330	807,210	806,960
	Furnaces	26,829	15,009	8,211	8,065
	Cogeneration	——	18,247	29,269	29,596
	Saving	——	1,393	3,289	3,358
Greenhouse-gas emissions ($kton_{CO_2-eq}$)	Central electric	27,556	27,096	26,726	26,713
	Furnaces	1,558	871	477	468
	Cogeneration	——	1,059	1,699	1,718
	Reduction	——	88	212	215

CO_2 emissions almost triples to 212 and 215 kton/year, respectively. When comparing the results of one large CHP facility and multiple small-scale facilities, it can be seen that the differences are small and even almost disappear when the thermal-storage capacity is increased. Certainly when the total amount of CO_2 emissions is considered, the differences are as good as negligible. Therefore, the approach of one large cogeneration unit, albeit fictitious, seems satisfactory.

4. Summary and conclusions

The first part of this paper discusses the dimensioning of cogeneration facilities to fulfil a certain heat demand and the impact of thermal-storage tanks on the operational behaviour of these units. In order to properly dimension residential CHP facilities, 40 different residential heat-demand profiles were created out of a set of measured data. The dimensioning itself was done by means of the 'largest rectangle' method. Subsequently, a parameterised CHP simulation model has been used to evaluate the impact of thermal storage on the operational behaviour of small-scale residential cogeneration facilities. Hereby it became clear that the effect of thermal storage is threefold: higher operating times, more continuous operation and the possibility for CHP facilities to operate for periods less than the time interval used in the simulation programme, namely 1 h. Furthermore, some interesting understandings regarding the correct interpretation of load-duration diagrams were raised. Briefly summarised, it all adds up to the chronological decoupling of the heat-demand and heat-production curves, so that it is impossible to draw any conclusions about the amount of heat that is stored or about the time when this stored heat is used. Finally, it was verified whether the overall behaviour of multiple small-scale CHP facilities could be approximated by the operational behaviour of one large fictitious cogeneraton unit.

In the second part of this paper, the impact of thermal storage on the overall CO_2 emissions was investigated. The net reduction of CO_2 emissions, compared to the reference scenario without additionally installed cogeneration, is directly coupled to the yearly operating time of the cogeneration units. Using a small thermal-storage device causes this net reduction to be almost three times as high compared with when no heat buffer is installed. Further increasing the size of the thermal-storage capacity, has only a minor effect on the CO_2-emission reduction, as CHP operating times remain practically the same. Furthermore, it became clear that the approach of using one large fictitious CHP facility is certainly satisfactory.

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